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Disruption of satellites in cosmological haloes

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Abstract. We investigate how the survival of dark matter satellites inside virialized halos depends on tidal stripping and dynamical friction. We use an analytic approach and then compare the results with N-Body simulations. Both the satellites and the primary halos are similar to cosmological haloes and have NFW density profiles. Satellites can either merge with the primary halo or continue to move on barely perturbed orbits, eventually being disrupted, depending on the relative strength of friction and tidal forces. We propose that their actual fate depends simply on their mass ratio relative to the primary halo.

1. Introduction

In the current view, galaxy formation occurs within dark matter haloes while these grow and evolve through a complex hierarchy of mergers. Understanding the dynamical evolution of haloes is thus essential in order to understand the evolution of galaxies. High-resolution N-body simulations show that small haloes, once they are accreted by a larger halo, can retain their identity and become substructures (Moore, Katz & Lake 1996; Tormen 1997; Ghigna et al. 1998). These substructures are affected by various dynamical mechanisms which can lead to their disruption. The dynamical friction drives the satellites towards the center of the primary system where they can ultimately merge. The tidal forces exerted by the primary halo cause the satellite to lose mass and can lead to its evaporation (Gnedin & Ostriker 1997; Gnedin, Hernquist & Ostriker 1999; Taylor & Babul 2000; Taffoni et al. 2001 in prep).

As it has been already pointed out in Colpi, Mayer & Governato (1999), a satellite can be disrupted before friction has eroded significantly its orbit. In

semianalytical models that attempt to trace the evolution of galaxies within haloes (i.e. Kauffmann et al. 1999; Somerville & Primack 1999; Cole et al. 2001), a merging event between two or more haloes corresponds to the complete loss of their identity and the galaxies within them are evolved as if they were detached from their original haloes. In particular, the possibility that one of them might be disrupted along with its halo is completely neglected by semianalytical models. Tidal disruption is instead known to be likely for other stellar systems subject to a strong tidal field, like the globular clusters in our Galaxy (Gnedin & Ostriker 1997). Clearly, the mechanism of disruption can be studied properly only taking into account the simultaneous effect of dynamical friction and tidal stripping.

2. The dynamical evolution in a NFW halo

The full dynamical evolution of the satellites must be studied for haloes analogous to those forming in cosmological simulations, here described by the so called NFW density profile (Navarro, Frenk & White 1996):

$$\rho(r) = \frac{M_{\rm v}}{4\pi R_{\rm v}^3} \frac{\delta_{\rm c}}{c\,x(1+c\,x)^2} \,, \tag{1}$$

where $x = r/R_{\rm v}$, $R_{\rm v}$ is the virial radius, $M_{\rm v}$ is the mass of the halo inside the virial radius and $\delta_{\rm c} = c^3/(\log(1+c) - c/(1+c))$ with $c = r_{\rm s}/R_{\rm v}$ ($r_{\rm s}$ is a scale radius).

In a spherically symmetric system the orbit is planar and can be determined using the planar polar coordinates $r(t)$ and $\theta(t)$ solving the equation of motion for the static NFW spherical potential ϕ (see e.g. Binney & Tremain 1987). The motion of a satellite is then determined by the initial angular momentum J and the orbital energy E which can be expressed in terms of the radius of a circular orbit with the same energy as the considered one $r_{\rm c}(E)$ and the circularity $\epsilon = J/J_{\rm c}$ ($J_{\rm c} = V_{\rm c} \cdot r_{\rm c}$).

2.1. Dynamical friction

During its motion, the satellite induces a perturbation on the density field of the primary halo; the net result of this distortion is a back-reaction force that decelerates the satellite driving it towards the center of mass of the main halo. In the limit of a uniform infinite collisionless background Chandrasekhar (1943) developed a simple theory to model this *dynamical friction force.* A body of mass $M_{\rm s}$ moving with velocity $\mathbf{v}$ relative to a background of stars with mass $m \ll M_s$ and density ρ, experiences a drag force

$$\mathbf{f}_{df} = -4\pi G^2 M_{\rm s}^2 \rho \, \log(\Lambda) \frac{\Xi(v/(\sqrt{2}\sigma))}{v^3} \mathbf{v} \,, \tag{2}$$

where σ is the one-dimension velocity dispersion of the stars, and $\Xi(x) = {\rm erf}(x) - 2x/\sqrt{\pi}\ \exp(-x^2)$ (see e.g. Binney & Tremain 1987). The normalization of the force is given by the so called *Coulomb logarithm* $\log\Lambda$. This is usually set as $\log\Lambda = \log(M_{\rm s}/M_{\rm halo})$ (Binney & Tremain 1987; Lacey & Cole 1993;

provided $M_s/M_{halo} \ll 1$). We treat the frictional drag on the satellite as local and consider $\rho(r)$ and $\sigma(r)$ as described by NFW. Dynamical friction in a non-uniform self-gravitating stellar background with NFW density profile is treated self-consistently using the theory of linear response (Colpi & Pallavicini 1998) in Taffoni et al. (2001).

2.2. Tidal effects

The overall effect of the tidal perturbation is the progressive evaporation of a satellite; this process takes place during the entire orbital evolution and it is generally sensitive both to the internal properties of the satellite and of the surrounding halo. We distinguish two tidal effects: a tidal truncation (*tidal cut*), originated by a steady tidal force, and a secular evaporation effect (*tidal shock*), induced by repeated gravitational shocks which take place internal to the satellite at each pericentric passage.

A satellite orbiting in a halo is tidally truncated at its tidal radius r_t which is defined as the distance of the center of mass of the satellite from the saddle point of the potential of the total system. Loosely speaking it corresponds to the radius at which the mean density of the satellite is of the order of the mean density of the halo within R (the distance of the two centers of mass): $\bar{\rho}_s(r_t) \approx \bar{\rho}_{halo}(R)$. Such radius will be a function of time if the orbit is perturbed by, e.g., dynamical friction.

At each periastron passage the satellite crosses very rapidly the central and more concentrated regions of the primary halo where tides are strongest, providing internal heating. Such kind of interactions are called tidal shocks (Spitzer 1978) and usually last a time small compared to the mean internal dynamical time of the satellite.

We will use the results derived by Gnedin, Hernquist, & Ostriker (1999) to describe the amount of heating due to tidal shocks. During an orbital period T the tidal force produces a global variation on the velocity of the internal fluid. This velocity change causes a reduction of the binding energy of the system, which is quadratic in the perturbation $\langle \Delta E \rangle = (1/2)\langle \Delta v^2 \rangle$. An important role is played by the *adiabatic corrections*: Gnedin, Lee & Ostriker (1998) (see also Weinberg 1994) showed that the effect of the tidal shocks can be properly modeled by multiplying the impulsive energy change ΔE for a correction which takes into account that the response of the stars can be adiabatic to a certain degree (i.e. the system can partially readjust to the time-dependent tidal field). The actual energy associated with the shock is reduced and reads:

$$\langle \Delta E \rangle_{act} = \langle \Delta E \rangle A(\omega\tau) , \tag{3}$$

where $A(\omega\tau)$ is a given function of the orbital frequency of stars $\omega(r)$ relative to the shock duration time τ.

At every periastron passage the satellites reduces its binding energy by an amount $\langle \Delta E_{hm} \rangle_{act}$ which is evaluated at the half mass radius of the tidally truncated satellite. As a consequence of this energy gain, the satellite expands and, eventually, evaporates.

To provide a convenient and simple parameter to express the intensity of the shock heating we define a characteristic time for disruption (see e.g. Spitzer 1987). The characteristic time is related to the number of periastron passages a

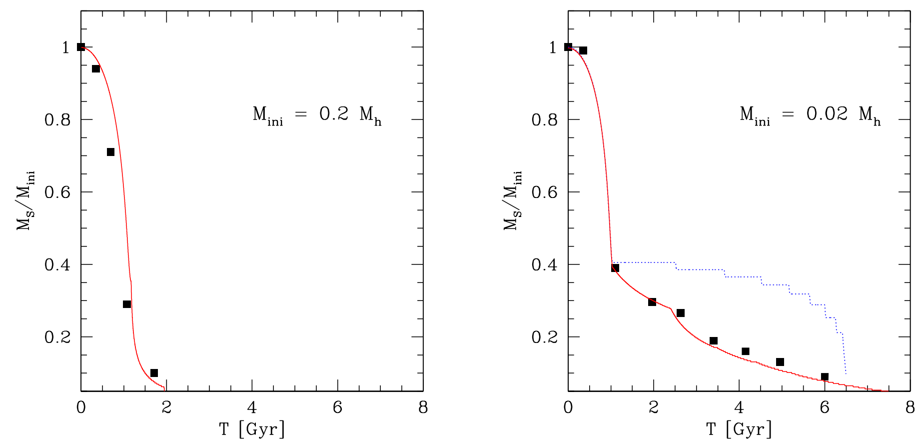

Figure 1. The instantaneous mass of a satellite for initial orbital parameters $\epsilon = 0.6$ and $r_c(E) = 0.5$ and for an initial apoastron $r = 0.74$ R_{vir}, where R_{vir} is the primary halo virial radius. The left plot shows the instantaneous mass normalized to the initial one for a satellite of initial mass 1/5 of the primary halo mass, the solid line is the analytical model and the points are the simulation data. The right plot shows the same quantity for a satellite of initial mass 1/50 the mass of the primary halo. The dotted line is the mass-loss for a satellite that experiences only the tidal truncation at pericenter.

satellite needs to reach the zero energy state and become unbound:

$$t_{\rm dis} = T \cdot \frac{E_0}{\langle \Delta E_{\rm hm} \rangle_{\rm act}} \ , \tag{4}$$

where E_0 is the binding energy of the already tidally truncated satellite evaluated at the half mass radius $r_{\rm hm}$: $E_0 = 0.25 G M_{\rm s,tid}/R_{\rm hm}$ (Gnedin, Lee & Ostriker 1999), (for all the detail of the calculation see Gnedin, Herquist & Ostriker 1999 and Taffoni et al 2001).

The rate of mass loss by the satellite due to tidal shocks can be written in terms of the characteristic disruption time as:

$$-\frac{1}{M}\frac{dM}{dt} \propto \frac{1}{t_{\rm dis}} \ , \tag{5}$$

(Spitzer 1987, pp. 115-117).

2.3. Tidal stripping with dynamical friction

The dynamical friction force is related to the mass and the size of the satellite, and it is highly affected by the mass loss induced by the tidal perturbation. While the satellite reduces its mass the drag force becomes less intense and the dynamical friction time increases. On the other hand the typical energy of the shock increases because the orbit shrinks due to dynamical friction. The two processes are thus strongly connected and cooperate to dissolve the satellite.

We consider a simple model in which a spherical satellite halo is orbiting inside a spherical primary halo, both being described by a NFW profile, with concentration $c_{\rm s} = 30$ and $c_{\rm h} = 15$, respectively. We follow the dynamical evolution of satellites on an orbit with initial orbital parameters $\epsilon = 0.6$ and $r_{\rm c}(E) = 0.5$. This particular combination of parameters is the most likley in a cold dark matter Universe (see e.g. Tormen 1997; Ghigna et. al 1998).

In figure 1, we show the results for two satellites, a light one with initial mass $M_{\rm ini} = 0.02 M_{\rm h}$, where $M_{\rm h}$ is the main halo mass, and a heavy one with $M_{\rm ini} = 0.2 M_{\rm h}$. During the first periastron passage both satellites are tidally truncated and reduce their mass of about 60 %. The amount of mass stripped by the background during this first phase of evolution depends on the initial orbital parameters and on the density profile of both the main halo and the satellite. Then, at each periastron passage, satellites are tidally shocked and they loose mass with a rate determined by eq. 5.

We compare the results obtained within our model with an N-body simulation performed with PKDGRAV, a high-performance parallel binary treecode developed by the HPCC group in Seattle (Dikaiakos & Stadel 1996; Stadel, Wadsley & Quinn, in preparation). PKDGRAV has multistepping capabilities which makes it ideal for following accurately and efficiently a rapidly varying density field like that typical of simulations with tidal interactions (see Mayer et al. 2001). We used 20.000 particles for the satellite and 50.000 particles for the primary halo. We note that a complete description that accounts for both the tidal truncation and the evaporation due to tidal shocks can reproduce with good accuracy the mass loss of the N-Body satellite; a simple tidal truncation is instead insufficient (see. figure 1, right plot).

3. Conclusions

The simple model presented allows to investigate the fate of substructures inside a dark matter halo. It is importnat to know if a satellite merges with the central object of the main system or it evaporates without interacting with any other halo; infact, the impact on the formation/evolution of host galaxies in both the primary and satellite haloes will be radically different in one or the other case.

We note that the dynamical evolution of a substructure is the result of the interplay between dynamical friction and tidal evaporation. We emphasize that a simple analytical model which does not include the tidal shocks cannot describe the dynamical evolution of the dark matter satellites properly.

The efficiency of the tidal disruption depends on the initial orbital parameters and on the density profile of both the primary halo and the satellite. Highly concentrated profiles induce a more intense tidal shock on the satellite. On the other hand, highly concentrated satellites will be more stable to evaporation, responding more adiabatically to the tidal field.

We explored a wide parameter space within our analytical model and ran several N-Body simulations for comparison.

We finally identified three different regimes in which the evolution of the satellites can take place:

1. High mass satellites ($M_\mathrm{s} > 0.2 M_\mathrm{h}$) reduce their mass but the efficiency of the dynamical friction is high enough to drive them to the center as if they were rigid. *Merging* is thus the fate of such satellites.

2. For low mass satellites $M_\mathrm{s} << 0.01 M_\mathrm{h}$, the dynamical friction time is longer than the Hubble time and the tidal evaporation will eventually disrupt such haloes on cosmological orbits. *Distruption* or *Survival* is thus the fate of such satellites depending on the value of their central density and on their average orbital radius.

3. For $0.01 M_\mathrm{h} < M_\mathrm{s} < 0.1 M_\mathrm{h}$ both the dynamical friction and tidal disruption contribute to the death of substructure. Satellites can decay substantially towards the center and merge, but only after a conspicious mass loss.

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